Summary of Thesis Work

X-ray Properties of Galaxy Groups and Clusters

by

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ABSTRACT

Active Galactic Nuclei (AGN), at the centres of massive galaxies, are believed to play significant roles on the evolution of their host galaxies through a process known as AGN feedback. Imprint of AGN feedback is best studied by observing the diffuse X-ray emitting gas inside the galaxy clusters and groups. Thus, it is essential to characterize the X-ray properties of the galaxy cluster/groups by modelling the X-ray emission from the hot gas inside them to interpret the signatures of feedback from AGN. To understand, a large range of observational results in this context, AGN feedback has been incorporated into cosmological hydrodynamic simulations in the last fifteen years. Throughout my thesis work, I have used cosmological simulation data in search for the imprint of AGN feedback on their surrounding environment and tried to understand the influence of it on the co-evolution of supermassive black holes with their host galaxies and dark matter halos.

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1. Introduction

Recent studies show that every massive galaxy in the Universe harbors a central supermassive black hole (SMBH) of mass ranging between $10^6 - 10^9 M_\odot$ (Soltan 1982). Some of them are active and they accrete gas from their neighborhood to grow. This class of SMBHs are known as active galactic nuclei (AGN). As they grow by accreting matter from their neighbouring environments, they release a large amount of energy into their surroundings. Some fraction of the radiated energy couples to the surrounding gas in a process known as AGN feedback (Silk & Rees 1998).

Many studies show that AGN feedback has observable effects on galaxy formation known as AGN-galaxy co-evolution in the literature (Kauffmann & Haehnelt 2000; Hopkins et al. 2006). Studies show that strong correlation exists between the central black hole mass and other galaxy properties such as stellar velocity dispersion (Ferrarese & Merritt 2000), bulge luminosity (Kormendy & Richstone 1995), bulge mass (Magorrian et al. 1998), Sersic index (Graham & Driver 2007), kinetic energy of the random motion of the bulge (Feoli & Mancini 2009), gravitational binding energy (Aller & Richstone 2007), virial mass of the galaxy (Ferrarese et al. 2006) etc.

Theoretical models of this paradigm of co-evolution has been explored by numerous groups (Granato et al. 2004; Monaco et al. 2007; Biernacki et al. 2017). All of these models explain the observed correlation in terms of strong feedback from the AGN (e.g., Silk & Rees 1998; Di Matteo et al. 2005; Yang et al. 2018). Theoretical studies have been also undertaken to explain the effect of AGN feedback on the surrounding hot gas in galaxy groups and clusters (Gaspari et al. 2012; Choi et al. 2015). To study the effect of AGN feedback on large scale structure and to evaluate its importance on the evolutionary history of the Universe, AGN feedback has been introduced in cosmological simulations (e.g., Di Matteo et al. 2008; Schaye et al. 2015; Davé et al. 2019; Nelson et al. 2019).

One of the hallmarks of AGN activity on its surrounding medium was observed by examining the properties of the hot X-ray emitting gas in galaxy groups and clusters (e.g., Wise et al. 2007; McCarthy et al. 2010; Vagshette et al. 2017). X-ray under-luminous regions of different spatial extents were observed from various observations in the galaxy groups and clusters (Fabian et al. 2006; Hlavacek-Larrondo et al. 2015; Lau et al. 2017). These X-ray cavities are proposed to be formed by the interaction of AGN jets with the hot X-ray gas in the intra-cluster medium (ICM) (O'Sullivan et al. 2010; Dong et al. 2010). Amongst other evidences, AGN feedback has also been inferred from the $L_X - T$ relation (Andersson et al. 2009; Maughan et al. 2012; Molham et al. 2020). Hence, X-ray observations have been proven to be one of the best avenues to understand the phenomenon of feedback from AGN.

In this work we use the MassiveBlack- II (MBII) cosmological simulations ran by Khandai et al. (2015)

to study a large representative volume of the Universe with a spatial resolution of $\sim few$ kpc. Using this simulation we investigate the effect of AGN feedback on their surrounding medium by evaluating the correlation between AGN activity with the properties of the intra-cluster medium (ICM) as well as the host dark matter halos of AGN. Besides, we investigate the X-ray properties of diffuse gas inside the clusters and groups of galaxies. For that, we model the X-ray emission from the hot gas surrounding the black holes within galaxy groups/clusters using the Astrophysical Plasma Emission Code (APEC: Smith et al. 2001). Finally, we perform the synthetic observation of the *Chandra* X-ray telescope to compare our results with direct observations of (Chatterjee et al. 2015; Mukherjee et al. 2019, M19 hereafter).

2. Simulation

For my thesis work, I have extensively used two sets of cosmological hydrodynamic simulations, ran by Di Matteo et al. (2008, hereafter D08) and Khandai et al. (2015, hereafter K15), based on the GADGET-2 and GADET-3 simulations(Springel 2005). The initial conditions and the cosmological modeling of both the simulations are same while only differing from each other by the box size and the spatial resolution. Parameters of both the simulations are listed in Table 1. These simulations are based on a Tree Particle Mesh - Smoothed Particle Hydrodynamics code, whose parameters are consistent with the ΛCDM cosmology. Due to limited spatial resolution of the simulation, formation of stars, AGN and the associated feedback from AGN have been modeled by the subgrid physics (Khandai et al. 2015; Di Matteo et al. 2008).

Black holes (BH) in the simulation are assumed as collisionless sink particles and they can grow in mass by accreting gas encompassing them or coalescing during the mergers. BH accretion rate in the simulation is determined by the Bondi-Hoyle-Lyttleton prescription (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944; Bondi 1952). The bolometric luminosity of the AGN is expressed as $L_{bol} = \eta \dot{M}_{BH} c^2$, where c is the speed of light and η is the radiative efficiency. The value of η is chosen to be 0.1 considering radiatively efficient thin disk accretion (Shakura & Sunyaev 1973). Part of the bolometric luminosity couples to the surrounding environment isotropically as the feedback energy. Deposition rate of the feedback energy is given by

$$\dot{E}_f = \varepsilon_f L_{bol} \tag{1}$$

where ε_f is called the feedback efficiency (Di Matteo et al. 2008). This value is adjusted according to the $M_{BH} - \sigma$ relation in the nearby galaxies and is fixed to 0.05 throughout the simulation (Di Matteo et al. 2005).

Although AGN feedback can be modeled and tested from various observations, the origin of seed SMBH is still unknown. Moreover the resolution of this simulation limits us to study their origin at the relevant length scales. For these reasons, a seed BH with a certain initial mass is inserted in a halo above a threshold

Simulation	Boxsize ($h^{-1}Mpc$)	N_p	$m_{DM}(h^{-1}M_\odot)$	$m_{gas}(h^{-1}M_\odot)$	$\varepsilon(h^{-1}kpc)$	z_{end}
D08	33.75	2×216^3	2.75×10^8	4.24×10^7	6.25	1
K15	100	2×1792^3	1.1×10^7	2.2×10^6	1.85	0

Table 1: The simulation parameters: N_p, m_{DM}, m_{gas}, ε, z_{end} symbolize the total number of dark matter and gas particles , mass of dark matter particles, initial mass of gas particles, gravitational softening length and the final redshift respectively.

mass which does not contain a black hole already. After that the seed black holes grow by accretion and mergers. Dark matter halos are composed of the dark matter particles grouped on the run by the friends-of-friends (FOF) algorithm. Subhaloes within them are determined following the SUBFIND algorithm (Springel et al. 2001). If a dark matter halo exceeds the mass of $\gtrsim 10^{10}h^{-1}M_{\odot}$ and still does not host a black hole, then its densest gas particles are converted into a seed black hole of mass $\approx 10^{5}h^{-1}M_{\odot}$.

One of the main motivations of my research is to study the effect of AGN feedback on their neighbouring X-ray emitting diffuse gas inside the galaxy groups and clusters by comparing with the scenario in which AGN feedback is absent. However, K15 did not run a simulation where AGN feedback is absent. So, to do the comparison, I have used the D08 simulation that both includes and excludes AGN feedback in the simulation starting from the same initial condition. Both the D08 and K15 simulations have been thoroughly compared with the results obtained from observations and they have successfully matched with the observed mass and luminosity functions of black hole, star formation rate as well as galaxy stellar mass function at different redshifts. An extensive discussion on the comparison of the simulated galaxy and AGN properties with the observational findings can be found in Khandai et al. (2015), Di Matteo et al. (2008).

To study the feedback effect on the gas ambient to the black holes, I consider a region of dimension $50h^{-1}$ kpc $\times 50h^{-1}$ kpc around each of them at z=1, equal to an angular scale of $\sim 3''$, which is the typical size of galaxies at that particular redshift. Corresponding systems where AGN feedback is absent are selected from D08 "without feedback" simulation matched by the mass and position of the host halo. X-ray maps of the diffuse gas inside these regions are constructed using the smoothed properties of the gas with the help of APEC. Finally, the synthetic observations of these regions are performed using MARX. The details of APEC and MARX are discussed in the next sections.

2.1. Simulating X-ray Maps Using Astrophysical Plasma Emission Code

I have used APEC (Smith et al. 2001), which is a spectral code used to model emission from hot, optically thin, colissionally ionized plasma, to calculate the X-ray flux emitted by the hot gas around the AGN in the soft energy (0.5 - 2.0 keV) band for this work. It is important to note that the X-rays coming from the central AGN is not considered in this analysis since I only wish to study the properties of the diffuse gas surrounding the SMBH. In the 0.5 - 2.0 keV energy range, line emission contributes significantly to the X-ray flux in addition to bremsstrahlung and the complete X-ray emission is incorporated in this work using APEC. In the study of real observation of the stacked signal of AGN feedback, M19 also chose only the optically selected AGN and discarded the ones that are detected in X-rays to avoid the contamination of the point spread function (PSF) of the signal from the central AGN.

The cosmological hydrodynamical simulations provide the position, temperature and metallicity of the gas particles. Smoothed parameters are computed according to the common B_2 smoothing spline :

$$W(x,h) = \frac{\sigma}{h^\nu}\begin{cases} 1-6(\frac{x}{h})^2+6(\frac{x}{h})^3 & \text{if } 0 \le \frac{x}{h} < 0.5 \\ 2(1-\frac{x}{h})^3 & \text{if } 0.5 \le \frac{x}{h} < 1 \\ 0 & \text{if } 1 \le \frac{x}{h} \end{cases}$$

where ν is the dimesionality and σ is the normalisation given by:

$$\sigma = \begin{cases} \frac{16}{3} & \text{for } \nu = 1 \\ \frac{80}{7\pi} & \text{for } \nu = 2 \\ \frac{8}{\pi} & \text{for } \nu = 3 \end{cases}$$

This calculates smoothed temperature and density profiles around the AGN. Then, I have divided the region of interest into spatial grids to calculate the X-ray flux and obtained the temperature (T), electron number density (n_e), proton number density (n_p) and metallicity (Z) for the particles inside these grids from the hydrodynamic simulation.

The X-ray flux arising from the i-th grid element is given by

$$j_i = n_{e,i} n_{p,i} \Lambda_E(T_i, Z_i) V_i, \tag{2}$$

where V_i is the volume of the grid element and $\Lambda_E(T,Z)$ is the X-ray emissivity from the APEC model at photon energy 0.5 - 2 keV. It is to be noted that the line cooling is incorporated in the X-ray emission with the metallicity used in the simulation. This generates the X-ray spectrum arising from that grid element in the soft band, which is integrated over the entire energy scale to get the total X-ray flux arising from that particular grid element. As the created maps are projections along the Z-axis of the simulation, the X-ray flux arising from the hot gas is calculated by adding the X-ray flux arising from all the grid elements along the projected direction.

After calculating theoretical X-ray flux, I plan to compare the results with actual observation in order to test the robustness of the simulation. For that, it is essential to incorporate the instrumental effects of the telescope involved in the observation into the theoretical results. I have done this by performing the synthetic observation of the *Chandra* X-ray telescope using our simulation data as discussed in the next section.

2.2. Construction of Synthetic X-ray Maps

I perform the synthetic X-ray observation of the diffuse gas in the galaxy groups and clusters surrounding the AGN in K15 and D08 simulation. This has been done using the portable simulator of the onboard *Chandra* X-ray Observatory (CXO) - Model of AXAF (Advanced X-ray Astrophysics Facility) Response to X-rays (MARX: Davis et al. 2012). This ray tracing simulator produces the event files of any observation. It is designed such that it accounts all the phases of a photon from incidence on the telescope mirror to its capture by the detector. MARX includes all the precise elements of the *Chandra* telescope, such as mirror of the telescope (High Resolution Mirror Assembly), the Advanced CCD Imaging Spectrometer (ACIS) detector of the spacecraft etc.

The event files of the mock observation has been analyzed in this work with the help of Chandra Interactive Analysis of Observations (CIAO) software (Fruscione et al. 2006). To perform mock observation with MARX, first of all the format of the input files are converted to the format supported by MARX followed by assigning the angular scale to those. Finally the photons are simulated using MARX for an exposure time of 200 ksec to qualitatively compare our results with observational work. All of the above mentioned steps are repeated for all the AGNs in the simulation satisfying the selection criteria and the resulting X-ray maps are co-added to obtain the stacked X-ray maps. The main motivation of studying the stacked X-ray map of the diffuse gas surrounding the AGN is to statistically examine the effect of AGN feedback on their ambient medium. This effect might not be detected in the individual systems due to the definite angular resolution of the telescope but it is expected to be observed in the stacked maps by enhancing the signal to noise ratio. Radial profile of the stacked X-ray maps are created both in the presence and absence of AGN feedback to explore this effect on their surrounding environment.

3. Global Effect of Feedback from Active Galactic Nuclei

In this work, I have examined the scaling relations between the properties of the SMBH and host halos and studied their redshift evolution. I propose the effect of AGN feedback on its surrounding medium as to explain these scaling relations and a probe to study the interaction of the SMBH with its environment. To do this, I focus on the diffuse gas as well as the total stellar mass inside the halos. Density and temperature distributions of gas surrounding the AGN clearly reveal the effect of AGN feedback on its surrounding environment. Here I briefly summarize and present the key results of this work.

For the current study, I use the K15 data for two redshifts ($z = 1.0$ and $z = 0.1$). Moreover, I select black holes which have mass $\geq 10^7 h^{-1} M_\odot$. As already discussed, the simulation inserts seed BHs of mass $10^5 h^{-1} M_\odot$ when halos have a mass greater than $10^{10} h^{-1} M_\odot$. These black holes then grow by accretion or merger. Thus, I prefer to limit the analysis of black holes with mass well above the seed black hole mass to minimize the numerical noise. The BH population has further been categorized into central and satellite BH at both the redshifts. To check the co-evolution of central SMBH and their host halo, I first examine the scaling relation between the host halo mass (M_{halo}) and the two black hole properties, i.e., mass (M_{BH}) and bolometric luminosity (L_{bol}). This is shown in Fig. 1. From the left panel, it is observed that the central BH mass is increasing with host halo mass at both $z = 1$ and $z = 0.1$ and we do not see any significant redshift evolution of this correlation. The satellite BH mass slightly increases and then gets saturated at the higher mass end of the host halos. The right panel depicts the variation of bolometric luminosity with the host halo mass of BH and it shows that with the increase of the halo mass, bolometric luminosty of the central AGN increases at both redshifts. But the satellite black hole luminosity is decreasing with the host halo mass.

The downsizing observed in the $\mathrm{L_{Bol} - M_{halo}}$ relation might be a hallmark of the effect of AGN feedback in the simulation. I argue that the outflow from the AGN is displacing the hot gas outward, thereby reducing the average density. So, the supply of cold gas gets cut inside the higher mass halo which results in the suppression of the BH mass and decreament of bolometric luminosity. Moreover, it is possible that the feedback from the central BH is regulating the growth of the satellite BH (e.g., Chatterjee et al. 2012). Similar result of the decrement of BH bolometric luminosity with its host halo mass has been observed by Richardson et al. (2013) from a completely different study. From clustering studies of AGN they showed that bright optically selected quasars with higher bolometric luminosity reside in lower mass halos compared to X-ray AGN with less luminosity.

To statistically investigate the effect of AGN feedback on the gas properties surrounding the black holes, I further make the gas temperature and density maps of dimension $50h^{-1}$ kpc $\times 50h^{-1}$ kpc around each BH and their without feedback counterpart and finally stack them. An example of temperature and density map

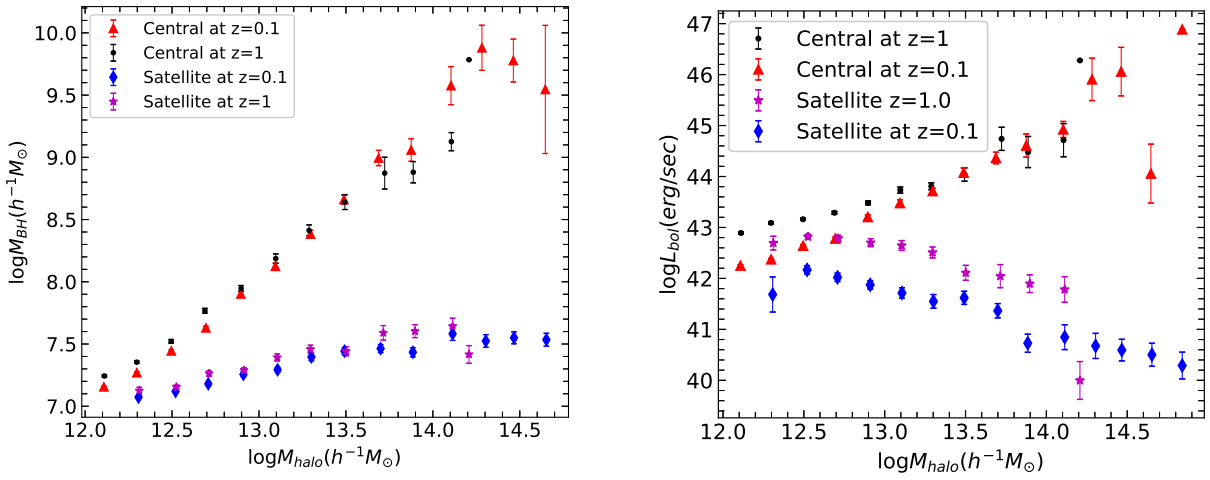

Fig. 1.— Left panel : $\mathrm{M_{halo}} - \mathrm{M_{BH}}$ relation in the K15 simulation at $z = 1$ and at $z = 0.1$. Black dots and magenta stars show the central and satellite black holes respectively at $z = 1$, while red triangles and blue diamonds represent the central and satellite black holes respectively at $z = 0.1$. Right panel : $\mathrm{M_{halo}} - \mathrm{L_{bol}}$ relation in the K15 simulation at $z = 1$ and $z = 0.1$. Color scheme is same as the left panel. The error on the data points are standard error, calculated as $\sigma/\sqrt{N}$, where σ is the standard deviation and N is the total number of data points in a particular mass bin.

of gas around a BH of mass $5 \times 10^7 h^{-1} M_\odot$ in K15 simulation at z=1 is shown in Fig. 2. Density (left panel) and temperature (right panel) radial profiles obtained from the stacked maps are shown in Fig. 3. Blue diamonds represent D08 without feedback simulation while red dots show the profile for K15 simulation. It is evident from this figure that density of the gas decreases statistically in the presence of AGN feedback. Moreover, right panel of the figure shows that presence of AGN feedback is enhancing the temperature of central region of the halo statistically. The overall enhancement of temperature and decrement of density of the gas inside all the halo supports the claim of feedback activity.

Finally, to check the effect of AGN feedback from a different perspective, stellar mass is plotted with the corresponding halo mass. Stellar mass, in our current work is defined as the total mass of the stars inside a radius which is equal to $0.2R_{200}$. R_{200} is the usual radius where the density of the halo becomes 200 times that of the critical density and the choice of radius for this work ($0.2R_{200}$) corresponds to tens of kiloparsec, a scale that we are interested in. This is shown in Fig. 4. It is clearly seen from the figure that the presence of feedback reduces the stellar mass when compared with the case of 'without feedback'. Also, it is seen that the stellar mass is higher at $z = 0.1$ compared to $z = 1.0$. I explain that AGN feedback heats the surrounding gas significantly, resulting in a depletion of cold gas, and thereby reducing the stellar mass in

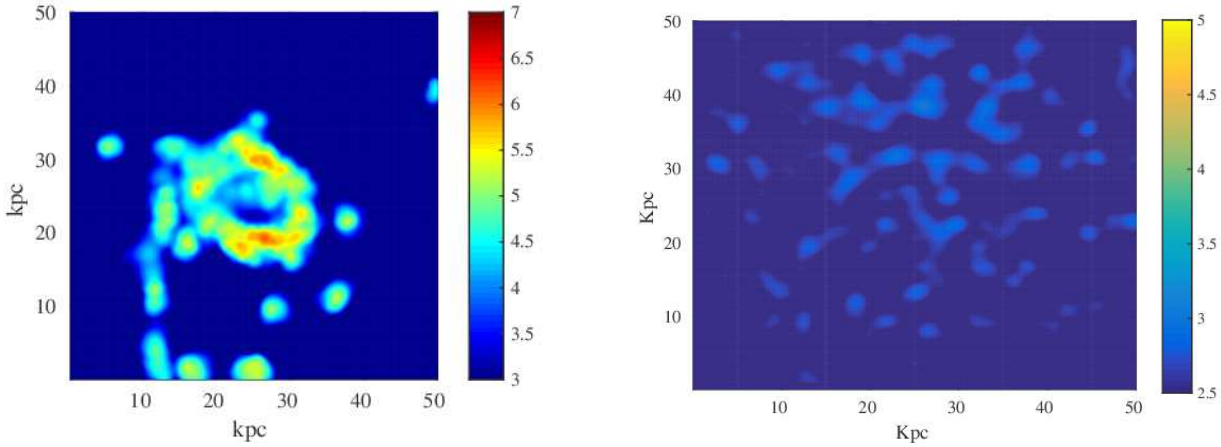

Fig. 2.— Density (left) and temperature (right) map of gas inside a region of radius 25 Kpc around a BH of mass $5 \times 10^7 h^{-1} M_\odot$. Left panel : colorbar represents density in $M_\odot/kpc^3$. Right panel : colorbar represents temperature in K.

the galaxy. Here I wish to clarify that the definition of stellar mass used in this work may be different from the other groups. For example, Khandai et al. (2015) define galaxies as the subhaloes consisting greater than 100 dark matter particles and their stellar mass is represented by the mass of the subhalos. In Torrey et al. (2014) stellar mass is defined as the total mass of the stars within twice the half-mass radius. However, taking this difference into account, it is noticed that feedback from AGN shuts down overall star-formation in its vicinity by limiting the availability of cold gas.

A plethora of work has been done by different groups to understand the growth of AGN and its effect on the surrounding medium. Using cosmological simulation cosmo-OWLS (McCarthy et al. 2014), Le Brun et al. (2014) showed that the density is lower at the central region of galaxy groups and clusters in presence of strong AGN feedback activity which is very similar to Fig. 3 (left panel). Also, the $M_{BH} - M_{halo}$ relation obtained by Le Brun et al. (2014) qualitatively agrees with the result of this study. In another recent work Le Brun et al. (2017) explored the scatter and evolution of the scaling relations between the properties of the hot gas inside galaxy clusters and their result for the evolution of the scaling relation between halo mass and bolometric luminosity agrees well with this work. In a different work by Barnes et al. (2017) using Cluster-EAGLE simulation, the density and temperature profiles of gas inside the clusters reveal that the gas is less dense and hotter at the central region in accordance with the claim of AGN feedback activity.

This study conclusively establishes the effect of AGN feedback and its implication on diffuse gas in galaxy groups and clusters. Starting from the effect of AGN feedback on its surrounding hot gas, I studied

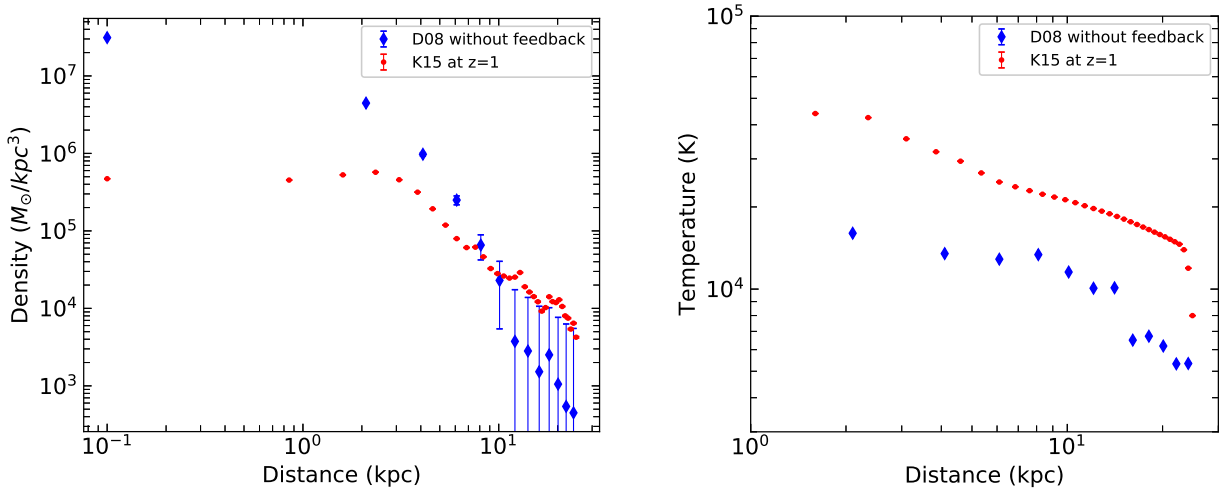

Fig. 3.— Left panel : Radial profile of the stacked density in presence and absence of AGN feedback inside a region of radius 25 kpc at $z = 1$. Right panel : Stacked radial profile of the temperature in presence and absence of AGN feedback inside a region of radius 25 kpc at $z = 1$. Blue diamonds represent the density profile when AGN feedback is absent in D08 and red dots show the scenario when AGN feedback is present in K15 in both the panels. Error bars on the data points in both the panels are the standard errors divided by the square root of the number of stacked maps to include the stacking error.

the evolution of AGN with their host halos. Some new observations are required to verify the claims presented in this work and I propose to conduct a detailed comparison between observed and simulated data in future. This work has been published in the Astrophysical Journal : **Kar Chowdhury, R., Chatterjee, S., Lonappan, A., Khandai, N., Di Matteo, T., 2020, ApJ, 889, 60, doi: 10.3847/1538-4357/ab5b96, Impact Factor: 5.58**

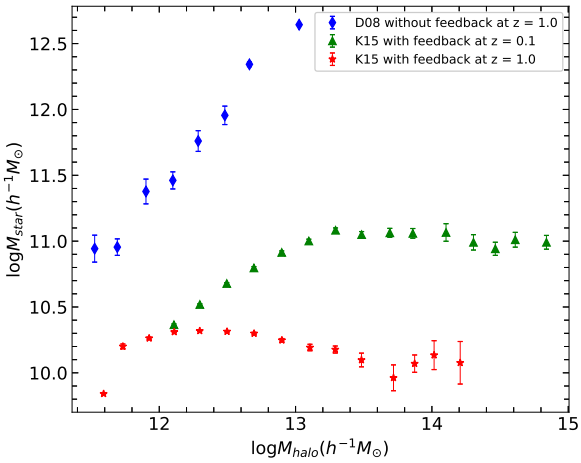

Fig. 4.— Variation of stellar mass with the corresponding halo mass bin. Blue diamonds represent the case when AGN feedback is absent in D08 simulation at $z = 1$. Red stars and green triangles are representative of K15 simulation at $z = 1$ and $z = 0.1$ respectively.

4. Characterization of X-ray Emission

In this work I focus on the characterization of X-ray emission from galaxy groups and clusters to better understand the influence of AGN feedback on its surrounding environment by performing mock *Chandra* observations and compare the results with existing observational results. Some of the previous studies employing the synthetic observations were done by Nagai et al. (2007), Mendygral et al. (2011) and Biffi et al. (2012). Biffi et al. (2018) studied the statistical properties of AGN from the synthetic observation of *eROSITA* using PHOX and compared their results with observations. Wilms et al. (2014) and Cucchetti et al. (2018) tried to examine the ICM properties observed with the mock *ATHENA* telescope. Currently, we statistically study a large sample of galaxy groups and clusters to investigate the signature of AGN feedback using a high resolution cosmological data that includes radiative gas cooling, formation of stars, and the feedback from supernova as well as from AGN and compare our results with direct observations of high redshift AGN. Here I briefly present the key results of this work.

For this work, I have used K15 simulation and D08 with and without feedback simulation to study the X-ray emission from the diffuse gas at z=1 in the presence and absence of AGN feedback. First I have selected regions of radii 25 h^{-1} kpc around each BH and their without feedback counterpart and model the diffuse X-ray emission from those regions using APEC. After that I perform the mock *Chandra* observation

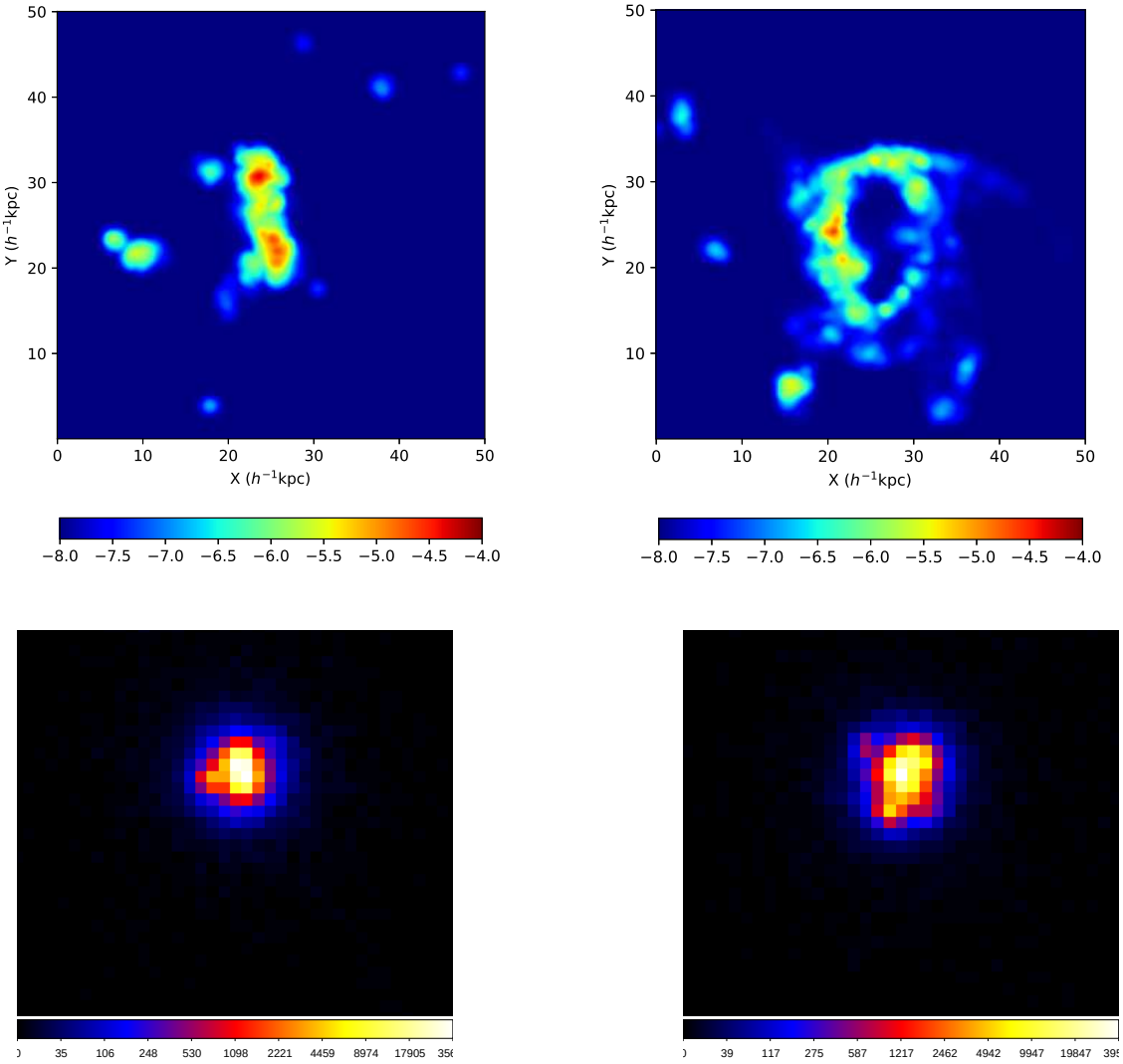

Fig. 5.— X-ray maps of the diffuse gas around two example AGN in the K15 simulation at z=1 inside the region of radius $25h^{-1}$ kpc. Upper panel: Theoretical X-ray maps around the AGNs, where the X-ray emission is modelled using APEC. Here the X-ray flux is color coded in the unit of $erg/cm^2/sec$. Lower panel: Synthetic *Chandra* X-ray maps inside the identical region ($\approx 3''$) around the same AGN. Here colorbars represent the photon number counts.

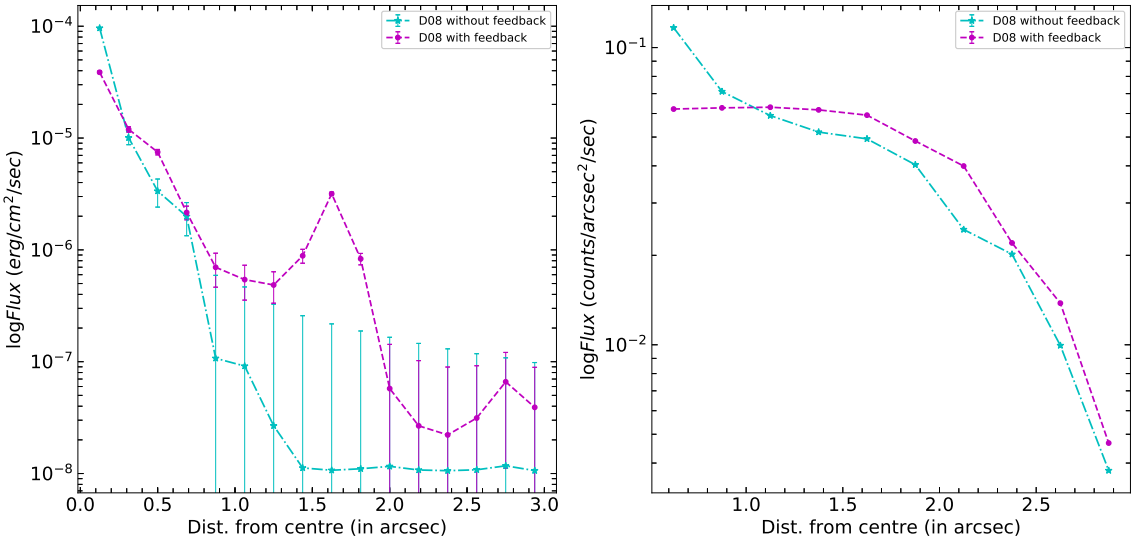

Fig. 6.— Stacked radial profile of the X-ray flux around the AGN at z=1 having $L_{bol} > 10^{43}$ erg/sec and their companion scenario in which AGN feedback is absent in D08 simulation. Left panel: Stacked radial profile of the diffuse X-ray flux calculated using APEC. Right panel: Synthetic stacked radial profile of the *Chandra* X-ray telescope for the same sample of AGN. Magenta dots and cyan stars in the both panel represent the scenario when AGN feedback is present and absent respectively in the simulation. Error bars on the data points are the standard errors at each annulus of the stacked maps.

of those systems using MARX as described before. Fig 5 shows the X-ray maps around two example AGNs in the K15 simulation at z=1. Top panel exhibits the theoretically obtained X-ray maps of the diffuse gas using APEC. Bottom panel represents the corresponding synthetic X-ray maps of *Chandra* telescope produced using MARX. Black holes are located at the centre of each image. It is observed that all the features of the theoretical X-ray maps disappear in the synthetically obtained maps. This could be explained as a result of the limited spatial resolution of the *Chandra* X-ray telescope, which is 0.5″. So, it becomes apparent that the signature of AGN feedback can not be detected from the observations of single systems.

Thus, I aim to study the effect of feedback from the central SMBH on their surrounding environment by performing a statistical analysis. To statistically study the signature of AGN feedback activity on the diffuse X-ray emitting gas, black holes are chosen from the D08 simulation and their counterpart in which the AGN feedback is absent. Theoretical X-ray emission around each AGN is calculated using APEC and the synthetic observation has been performed for all the systems and the resulting X-ray photon maps have been stacked to get the average radial profile of the diffuse X-ray flux in the presence and absence of AGN feedback. This is shown in Figure 6. Left panel shows the stacked radial profiles of the diffuse X-ray emission

modelled using APEC while the right panel represents the stacked radial profile of X-ray flux obtained from the mock *Chandra* observation. A central excess of the X-ray flux in the absence of AGN feedback is clearly noticeable in both the panels. This hints towards the fact that feedback from the AGN is displacing the X-ray emitting gas from the centre of the galaxy groups and clusters, resulting in underluminous regions in the X-rays. This agrees with the claims made in other previous studies that AGN feedback is displacing the surrounding gas outward (e.g., Gaspari et al. 2011; Pellegrini et al. 2012; Mukherjee et al. 2019). However, the stacked radial profile in case of the synthetic observation is smoothed due to the point spread function (PSF) of the *Chandra* telescope.

In our work, I have used two sets of high resolution cosmological simulation to generate a large statistical sample of synthetic X-ray observations of galaxy groups and clusters. Effect of feedback on X-ray images and profiles of groups and clusters is shown with active black holes at their centers. AGN feedback has been an important component in understanding galaxy evolution as well as cluster formation. Through the numerical and statistical work I demonstrate the new observational directions in which this interesting phenomenon can be studied through current and upcoming missions. This work has been accepted for publication in the Astronomische Nachrichten : **R. Kar Chowdhury, S. Roy, S. Chatterjee, N. Khandai, C. Sarazin, T. Di Matteo, 2020, AN, doi: 10.1002/asna.202113899, Impact Factor: 1.064**

In a consequent work, I am trying to validate the method of X-ray stacking in detecting feedback from systems that can not be resolved with current X-ray telescopes. Recently, M19 studied a population of high redshift optically bright AGN and a control sample of galaxies, and stacked the X-ray maps of the hot gas surrounding them to increase the signal-to-noise ratio in order to detect AGN feedback features if any. I am trying to examine the validity of their stacking analysis by peforming a similar co-adding techniques using synthetic observations and compare the result with that obtained from cosmological simulations. I have calculated ratio of feedback energy to that of the bolometric luminosity of the AGN and used this observable for comparison in order to validate the technique of M19. Draft of this work is in advanced stage and to be submitted to the Monthly Notices of the Royal Astronomical Society.

5. Ongoing and Future Research Work

My future research plans are broadly focused around testing X-ray simulations against observations to test the fidelity of my work and infer more about the role of AGN activity in galaxy evolution. However, I also plan to analyze the direct observational X-ray data to compare my results with those. Because a solid understanding of both data and simulations is essential to have deeper insights into outstanding the problems I am interested in pursuing.

One of the major directions of my future work will involve developing tools for mock observations of galaxy clusters and AGN feedback for existing telescopes (e.g., *eROSITA*) and upcoming X-ray missions (e.g., *Athena, XRISM*) starting from large scale cosmological simulations. Comparing theoretical results with the synthetic observations will provide insight about the effects of the telescope instruments on the actual observation which will help to deconvolve the instrumental response from the direct X-ray image and extract the information from them. It is also possible to study the detection probability of the upcoming X-ray missions by performing mock observations with them. Besides, the amount of data from the new surveys will be overwhelming, and it is still unknown how to best analyze such data. Mock observations will provide the necessary testing ground for different techniques.

To perform synthetic observations, at first photons are produced from the simulation and projected onto the sky coordinates. To create a photon map, I have used the python package pyXSIM [1]. Once the photon map is produced, it is convolved with the instrumental response function of the telescope to create a synthetic map. For the synthetic observation with *Athena* telescope, its instrumental response function can be incorporated using the software package SImulation of X-ray TElescopes (SIXTE: Dauser et al. 2019).

I have already developed the basic environment to work with SIXTE using MB-II data. However, MB-II suffers from a few limitations discussed in Kar Chowdhury et al. (2020). Thus, I plan to use different cosmological simulations to study the robustness of our technique. For this purpose, I plan to use data from cosmological hydrodynamic simulation Illustris-TNG (Nelson et al. 2019) and SIMBA (Davé et al. 2019). These state-of-the-art high resolution simulations consider the AGN feedback model in detail incorporating both the kinetic and radiative mode of feedback. Thus it is possible to compare the results of Illustris-TNG, SIMBA and MB-II to study the effect and importance of different AGN feedback processes on the diffuse X-ray gas inside galaxy clusters. We can also perform mock observations for different redshifts and study the redshift dependence of AGN feedback on their surrounding medium.

Besides, I have also planned to study the X-ray spectra of the AGN host galaxy clusters and compare

[1] http://hea-www.cfa.harvard.edu/ jzuhone/pyxsim/index.html

them with the normal galaxy clusters from the simulation to examine the signature of AGN feedback. Upcoming X-ray mission *Athena* is expected to revolutionize the field of X-ray spectroscopy with its extremely large field of view and great spectral resolution. It is capable of detecting weak spectral lines much better than the existing telescopes and also able to produce high resolution spectra of the extended sources (Barcons et al. 2012). I aim to model the X-ray emission from the simulated galaxy clusters using the APEC. In addition to the primary X-ray emission in galaxy clusters, which is thermal bremsstrahlung radiation, cooling by the metal lines are also important. Hence the X-ray spectra modeled using the simulated data would be more realistic if they consider different metal elements. In the recent simulations like Illustris-TNG and SIMBA, cluster environment is populated with various metals (H, He, C, N, O, Ne, Mg, Si and Fe) through the supernovae and AGB stars. I plan to study the X-ray spectrum of the diffuse gas in the galaxy clusters using the Illustris-TNG simulation data in search of the AGN feedback signature in them.

Understanding the role of AGN feedback on the evolution of their host galaxies and dark matter halo by studying the global properties of ambient hot gas and analysing various observables makes the fundamental objective of my thesis. In future I want to examine the diffuse X-ray emitting gas inside galaxy groups and clusters from both the theoretical and observational ground for a stonger validation of the AGN feedback scenario.

List of Publications

Following is the list of my refereed publications -

1. *Cosmological Simulation of Galaxy Groups and Clusters - I : Global Effect of Feedback from Active Galactic Nuclei*
   R. Kar Chowdhury, S. Chatterjee, Anto. I. Lonappan, N. Khandai, and T. DiMatteo, 2020, The Astrophysical Journal, 889, 1 (click here to go to the paper).

2. *Simulated X-ray Emission in Galaxy Clusters with AGN Feedback*
   R. Kar Chowdhury, S. Roy, S. Chatterjee, N. Khandai, C. Sarazin, T. Di Matteo, 2021, Astronomische Nachrichten, doi:10.1002/asna.202113898 (click here to go to the paper).

Following is the list of the conference proceedings (refereed) -

- *Cosmological evolution of supermassive black holes*
  S. Chatterjee, **R. Kar Chowdhury**, 2019, American Institute of Physics conference proceedings, Volume 2109, id.090004 (here)

List of Talks and Posters

Following is the list of my talks and posters presented at different conferences -

1. Contributed talk on "*Simulated X-ray Emission in Galaxy Clusters with AGN Feedback*" at the video conference of 9^{th} International Workshop on Astronomy and Relativistic Astrophysics, 2020 (find the participants list here and read the abstract here).

2. Contributed talk on "*Simulated X-ray Emission in Galaxy Clusters with AGN Feedback*" at the 236^{th} virtual meeting of the American Astronomical Society (AAS), 2020, Bulletin of the American Astronomical Society, 236, 124.05 (here)

3. Contributed talk on "*Signature of AGN Feedback From Cluster X-ray Emission*" in the 37^{th} annual meeting of Astronomical Society of India (ASI), Bengaluru, India, 2019 (find the participants list here and read the abstract here).

4. Contributed talk on "*X-ray Surface Brightness Profiles of Simulated Galaxy Groups*" in the 7^{th} Topical Conference on Gravity, Cosmology and Astrophysics (Eastern Region), Indian Association for the Cultivation of Science, Kolkata, India, 2017 (find the presentation and participants list here).

5. Contributed talk on "*X-ray Surface Brightness Profiles of Simulated Galaxy Clusters/Groups*" in the Young Astronomers' Meet (YAM), IUCAA, Pune, India, 2017 (find the list of participants here).

6. Poster on "*X-ray Properties of Galaxy Groups*" in the 35^{th} annual meeting of Astronomical Society of India (ASI), Jaipur, India, 2017 (find the participants list here and read the abstract here).

Following is the list of invited talks presented at different universities -

- "*Signature of Feedback from Active Galactic Nuclei in Galaxy Clusters : Numerical Simulations and Observations*" at Leiden Observatory, Leiden, the Netherlands, 2019.
- "*Signature of Feedback from Active Galactic Nuclei in Galaxy Clusters : Numerical Simulations and Observations*" at Kapteyn Astronomical Institute, Groningen, the Netherlands, 2019.
- "*Signature of Feedback from Active Galactic Nuclei in Galaxy Clusters : Numerical Simulations and Observations*" at University of Cologne, Cologne, Germany, 2019.

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